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TECHNICAL REPORT BRL-TR-3209

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LABORATORY INJECTOR FOR SPRAY STUDIES RELATED TO LIQUID PROPELLANT GUN

AVI BIRK
GARY BLIESENER

FEBRUARY 1991

U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

NOTICES

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
February 1991

3. REPORT TYPE AND DATES COVERED
Final, Jan 88 - Jan 91

4. TITLE AND SUBTITLE
Laboratory Injector for Spray Studies Related to Liquid Propellant Gun

5. FUNDING NUMBERS
PR: 1FVM9Y9XA450
DA31-2750

6. AUTHOR(S)
Avi Birk
Gary Bliesener

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Ballistic Research Laboratory
ATTN: SLCBR-DD-T
Aberdeen Proving Ground, MD 21005-5066

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
BRL-TR-3209

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

For the purpose of studying on a laboratory scale injection processes typical of a Regenerative Liquid Propellant Gun (RLPG) an injector (patent pending) has been constructed and tested successfully. A computer code was written for prediction of the injector performance. The injector operates on the RLPG injector principle. It features internal gas chambers and accessories which enhance its operational controllability. The injector is capable of injecting circular as well as annular jets. With HAN-based liquid propellants, the injector is capable of injecting 3-mm-thick jets with velocities in the range of 100 to 300 m/s and mass flow rates of up to 10 kg/s. This report describes the construction of the injector, its principle of operation, and its performance.

14. SUBJECT TERMS
Injectors; Regenerative Gun; Liquid Gun Propellants

15. NUMBER OF PAGES
44

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
UNCLASSIFIED

18. SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

19. SECURITY CLASSIFICATION OF ABSTRACT
UNCLASSIFIED

20. LIMITATION OF ABSTRACT
UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

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ACKNOWLEDGEMENT

The authors thank William F. Donovan for making all of the engineering drawings for fabrication of the injector, and for his assistance with the fine details of the design.

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I. INTRODUCTION

In recent years, the Regenerative Liquid Propellant Gun (RLPG) technology[1] has outpaced the insight into the complex physics of its underlying injection/combustion process. A major conclusion from earlier research using relatively simple laboratory test fixtures[2] was that a more advanced injection/combustion facility[3] had to be constructed if further insight was to be gained. In particular, an emphasis was placed on constructing an injector which would be flexible enough to allow both fundamental work with simple jet geometry, e.g. circular (which is easier to model), and with more practical annular jet configurations having dimensions approaching those of common 30-mm RLPG fixtures. Thus, requirements for the injector called for jets with thicknesses of 1 to 3 mm to be injected at velocities up to 300 m/sec into ambient pressures exceeding 25 MPa. A desired flexibility was that the injection velocity could be varied during the injection. Clearly, the injector to be constructed would be of the pressure atomizing type. Common laboratory injectors of this type employ a stepped differential area piston. The larger area is acted upon from a low pressure, large external reservoir while the smaller area, amplifying the reservoir pressure, acts on the injected liquid. Such injectors are not attractive as they become very bulky if high injection velocities are to be sustained from large injection ports, such as annular ones. Also, such injectors can not provide varied injection velocity profiles. From a safety point of view, when dealing with liquid propellant (LP) jet combustion tests, a sudden rise in ambient pressure would result in a drop of differential injection pressure, hence risking flash back into the injector.

In contrast, an RLPG type injector is a compact injector with high mass flow rates which inherently responds by increasing the injection pressure when the ambient pressure suddenly rises. Thus, considering the alternatives and bearing in mind that the type of injection process to be studied is that of an RLPG, it was decided to construct an RLPG type injector for laboratory use. The RLPG injector utilizes the ambient pressure for its operation but, depending on its design, may lack controllability over the initiation of the injection. For laboratory use, the proposed injector had to be initiated at any desired initial ambient pressure. This was solved by constructing an injector that employs a pressurized gas chamber as a counter balance against the ambient pressure. Control over injection initiation and injection velocity profile is achieved by controlling the pressure discharge from the gas chamber. This report details the structure and performance of the injector which was constructed for use in the BRL Spray Research Facility[3] (SRF). The injector features compactness, rapid response, circular as well as annular jet configuration, good controllability, and safety of operation. To date, the injector has been tested successfully in all configurations at 25 MPa ambient pressure. LP combustion tests[4] have been conducted featuring volumetric flow rates of up to 1000 cc/sec for total injected volumes up to 92 cc.

The purpose of this report is to serve as a manual for the operation of the injector and as a reference in future reported work from the SRF. The reader is also given the computer code which is used for the prediction/validation of the injector performance. The information contained herein may enable researchers to construct similar injectors and adapt them to their own uses. Presently, a patent is pending on the injector.

II. INJECTOR STRUCTURE AND OPERATION

A simplified assembly drawing (drawn to scale) of the injector is shown in Figures 1a, 1b, and 1c. An exploded view of the injector is depicted in Figure 2. The major parts and features of the injector are identified on both Figures 1 and 2. The injector has three modes of operation K, J, and L. The basic mode, K, generates a circular jet while modes J and L generate annular jets. All modes consist of four major part assemblies 1, 2, 3, 4 and chambers 'A, B, C' (and 'D' in case of modes of J and L) which contain the fluids involved with the operation of the injector. Chambers 'A' and 'D' contain liquid while chambers 'B' and 'C' contain gas (typically nitrogen). Chamber 'B' is shown in the closed position in Fig. 1a. All other parts are assembled into parts 1, 2, 3, and 4. Part 1 is the outer housing of the injector and is sealed against the bottom of the test chamber walls 30, thus forming the base of test chamber 'T' into which the liquid is injected through port 'j'. Part 2 forms the base of the injector into which all gas supplies are connected. Part 3 (or 3^* in modes J, L) is the injector outer piston. Part 4 (or 4^* in mode L) is the injector inner piston. Parts 1, 2, and 4 are stationary while part 3 is mobile. The liquid to be injected is contained in chamber 'A' which forms between 3 and 4. The maximum injection volume is 92 cc for mode K and 45 cc for modes J and L. Piston 4 is held on top of 2 by the pressure P_L in 'A'. The injector parts which are exposed to the liquid are made of stainless steel 316. Other parts are made of stainless steel 17-4PH. The injector is designed for 70 MPa differential injection pressure. The external gas controls for the injector will be detailed in reference 5.

The principle of operation of the injector is similar to that of of the RLPG. For its operation, it is required that a pressure P_C be established in 'T'. Due to the differential areas of part 3, a pressure P_L is formed in 'A' which causes the liquid in 'A' to be injected through 'j'. With the absence of pressures in 'B' and 'C', the differential area of 3 results in $P_L = 2.29\ P_C$ in Modes K and J, and in $P_L = 2.00\ P_C$ in Mode L. Unlike the RLPG, the subject injector has two gas chambers 'B' and 'C' which serve respectively to augment or arrest the motion of 3 by changing the force balance on 3. During injection, the piston 3 moves downward which decreases the volumes in 'A' and 'C' (and 'D' in mode L) and increases the volumes in 'B' and 'T'. Adding pressure in 'B' and 'T' while decreasing the pressure in 'C' will result in an increase in P_L and higher injection velocity. The detailed physical formulation of the injector operation is given in Section III. Following are the details concerning the injector subassemblies and operation. Mode K is discussed first.

Housing 1 contains the exhaust port for 'T' - 'exh'. The pressure in 'C' is monitored by a 601B1 Kistler pressure transducer - 'p'. Three pins 5 provide a stop for 3 when 30 is lifted away from 1. When assembled into 'T', 3 is stopped against 30 by 6. Pins 5 also prevent 3 from rotating while in longitudinal motion as they protrude into vertical tracks machined into 3. Part 2 contains all the gas ports leading into chambers 'B' and 'C'. 'C' is filled with gas via the port 'chg' and discharged via port 'dcg'. A port 'aug' is used to fill chamber 'B' (and also to discharge it after injection). Another port, not shown, is used to relieve gas or liquid leaks which may occur across the seals between 4 and 10 and between 2 and 4.

Three subassemblies are mounted into 2. The first of which, 15, is used to record the piston motion. A tapered shaft 14 screws into 3 and passes through 2 and 15. Camshaft mechanism 32 changes proximity to a Hall effect magnetic sensor 16 (Wolff Microjector) which results in a voltage output polynomially fitted to the vertical position of piston 3. Thus, piston velocity, chamber volumes, and therefore injection velocity can be easily calculated as a function of time.

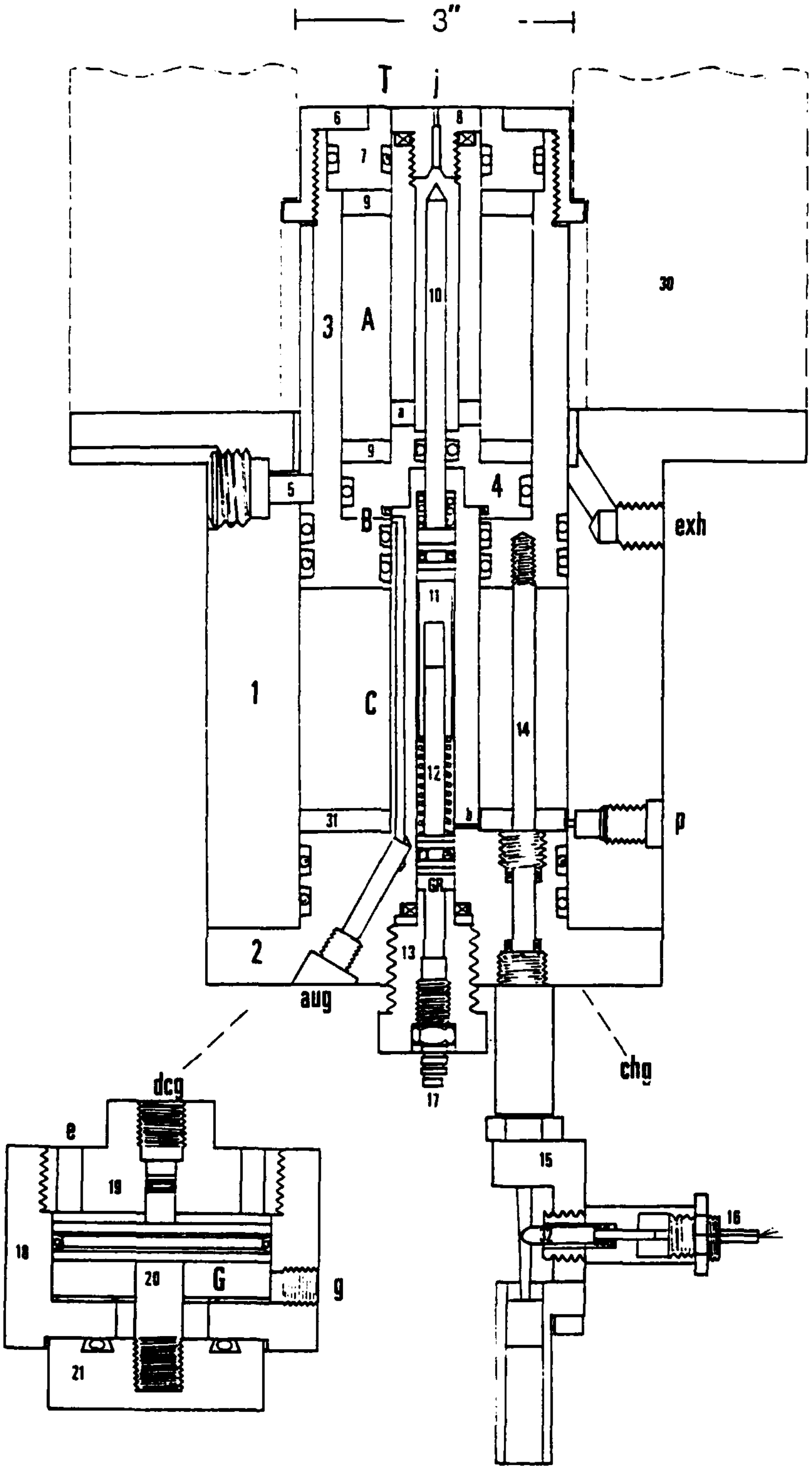

Fig. 1 a: Basic injector layout with mode K circular geometry.

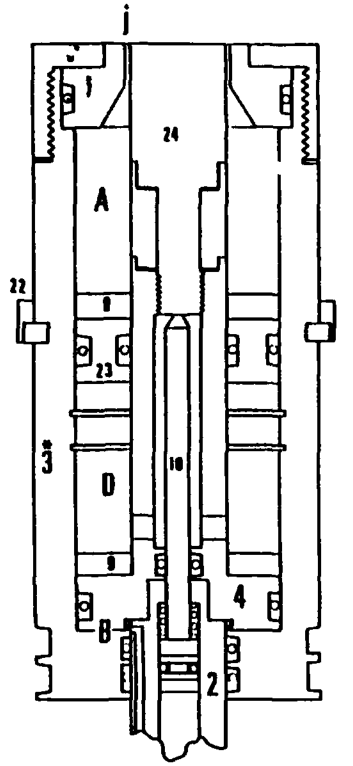

Fig. 1 b: Injector attachment for annular geometry mode J.

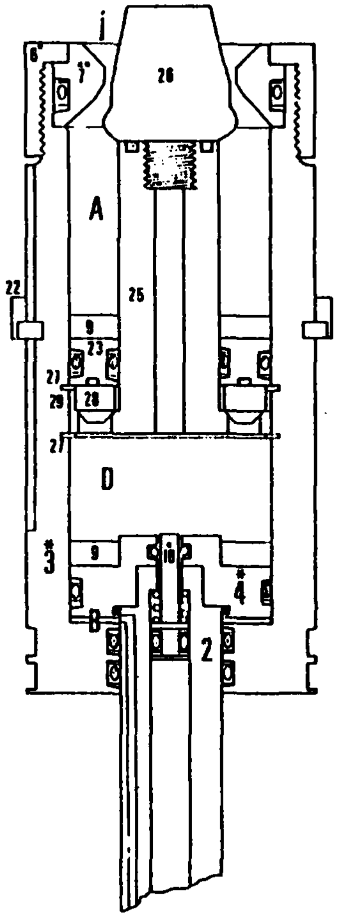

Fig. 1 c: Injector attachment for annular geometry mode L.

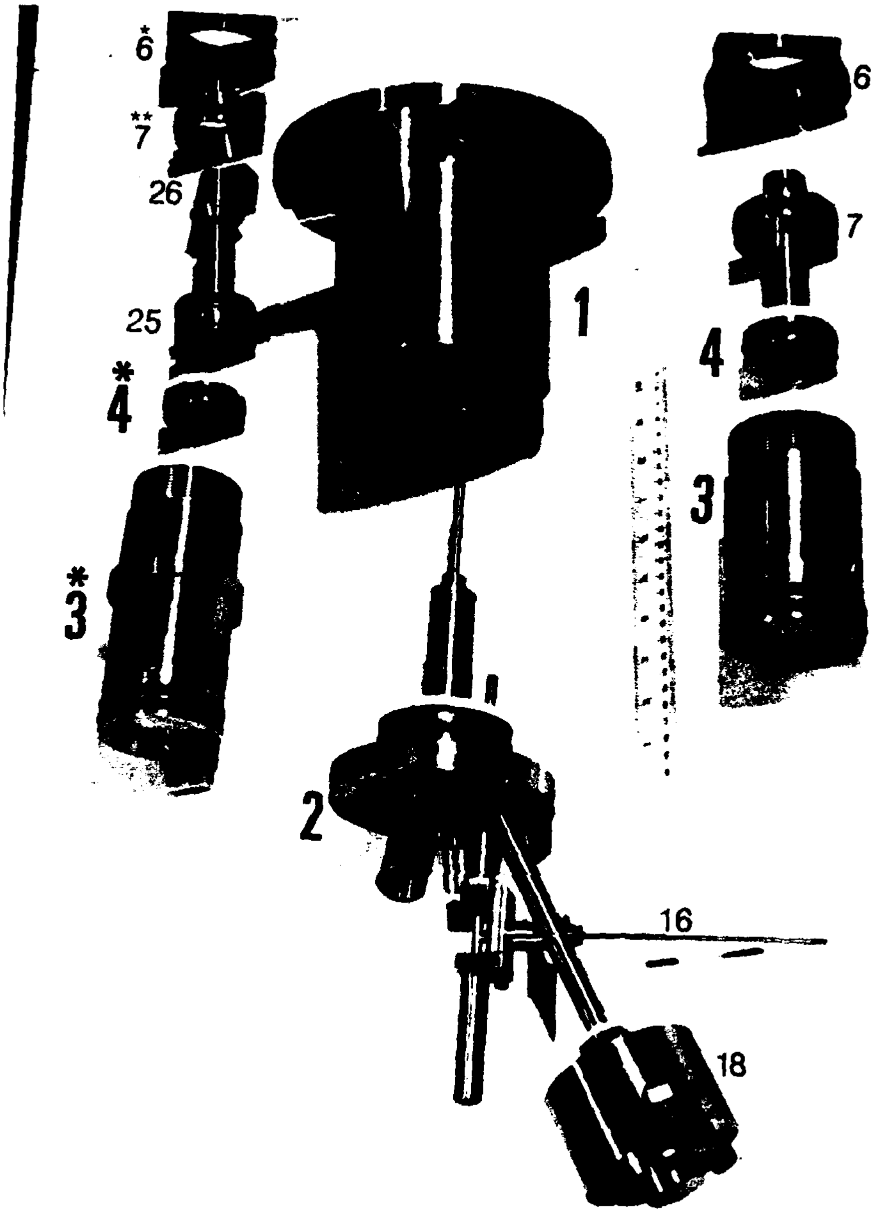

Fig. 2: Exploded view of injector parts.

The second subassembly is an ultra-fast exhaust valve connected to port 'dcg'. Part 19 is connected to port 'dcg' by the stainless steel tube shown in Fig. 2. The valve has a differential area stepped piston 20, an upper cup 19, housing 18 and a bottom plug 21. In its closed position, piston 20 is pushed into 19 such that 21 seals against 18. A low pressure (typically 0.8 MPa) is introduced from the laboratory air supply through 'g' into G. The piston 20 then presses 21 onto 18 thus strengthening the seal against 18. The pressure in G is sufficient to overcome the pressure P_H (the pressure in 'C') which exists in 19 and exerts on 20. Discharge of the pressure in G through 'g' results in 20 moving under P_H and instantly unseating 21 from 18 which results in a prompt discharge of the gas in G through the gap forming between 21 and 18. As 20 accelerates downward, its upper step departs 19 and the gas from 'C' is suddenly discharged through port 'e'. Various orifices can be mounted in 19 in order to control the discharge mass flow rate from 'C' through 19. This controls indirectly the injection velocity by virtue of regulating P_H. In its fastest release mode (i.e. no restricting orifices), the valve provides an instant (sub-millisecond) opening of .200 inch effective diameter. Such an ultra-fast valve is necessary in order to provide the required wide range of injection flow rates and velocity profiles.

The third subassembly mounted into 2 serves a dual role: sealing the injection port 'j' prior to injection and providing a means for measuring both port 'j' opening and pressure P_L. (A Kistler 607C3 pressure transducer 17 is mounted into plug 13 and measures P_L.) A grease column 'GR' between 17 and piston 12 transmits to 17 the pressure which is exerted on 12. Prior to injection, the piston 3 is in its uppermost position as defined by 6 exerting on 30 (a spacer, not shown, may be placed between 6 and 30 which results in a smaller initial 'A' and 'C' and larger 'B'). The gas in 'C' enters the void between 12 and 11 via passage 'b'. Pilot shaft 10 lifts under P_H until it seals against 8 thus preventing injection. The area ratio across 10 is such that a $P_L > 2.25\ P_H$ is required in order to unseat 10 from 8. When the pressure P_H is discharged through 'dcg', 10 retracts from the injection port and exerts force on 12 via 11 which translates into pressure measured by 17. Therefore prior to injector port opening, 17 measures P_H. As 11 contacts 12, 17 measures P_L, though indirectly. When 11 contacts 12, P_H is exerted equally on the bottom of 10 and on the top of 12, thus the net force felt by 17 is solely due to P_L exerting on the portion of 10 above its seal in 'A'. Prior to injection, 10 serves to insulate the combustible liquid in 'A' from the high temperature gas in 'T'. It also delays piston 3 motion until the pressure P_H drops below P_L / 2.25, thus resulting in higher initial injection velocity. Part 10 exposes 'j' in a controlled manner, thus resulting in a smooth injection initiation. The injector can also be operated with shaft 10^* (Fig. 1c) instead of 10. This will be referred to as "no shaft" opening mode (as opposed to "pilot shaft"). Piston 3 will, in this case, start its motion when $P_H < P_C / 1.71$.

In order to refill chamber 'A' with liquid, 30 is lifted from 1, and 3 is pushed to its desired position by applying some pressure in 'C'. Cap 6 and upper plug 7 are removed as well as teflon barrier 9. An injector plug 8 (with a selected diameter for injector port 'j') is screwed onto 4. The liquid is poured into volume 'A' which includes passage 'a' and the space around 10. A bleed hole (not shown) exists in 7. Parts 6, 7 and 9 are reassembled and the bleed hole plugged. During injection, 3 moves downward, thus displacing the liquid from 'A' via 'a' around 10 and injecting it into 'T' via 'j'. Barriers 9 serve as piston guides and also as insulation between the liquid and moving seals. This is a safety precaution for the cases when the liquid is LP. For spray combustion tests a water layer may be placed on top of the LP in 'A' below the upper barrier 9. A thin mylar barrier may be used to separate the LP and water. As the LP is displaced from 'A', the water flushes 'A' and prevents ignition in 'A' when the piston 3 is brought to a halt by rubber/teflon shock absorber 31.

Mode J (Figure 1b) operates virtually the same as mode K. The piston 3^* is similar to 3 in mode K, it is just longer. The injection port 'j', formed between 24 and 7^*, is annular and unlike mode K, it is not sealed from 'T' prior to injection. Piston 3^* is held against 30 by split ring 22. A floating piston 23 separates water in 'D' from the injected liquid in 'A'. It also supports the motion of 3^* along 4. The annulus thickness is varied by replacing 7^* with a part of a different inner diameter. The operation of mode J results in an injection pattern much like RLPG concept VI where a center body 24 is exposed as the piston 3^* retreats. Piston 3^* will start its motion when $P_H < P_C / 1.71$.

Mode L (Figure 1c) was constructed in order to simulate RLPG concept VI-C. The injection port is also annular. Here no center body is exposed as the piston retreats. Cap 26 has a geometry similar to the one found in a 30 mm RLPG concept VI-C. Cap 26 is mounted on pedestal 25 which is held into 3^* by means of snap rings 27 and spacer 29. Water fills volume 'D' while the injected liquid fills volume 'A'. The motion of 3^* displaces the water from 'D' which pushes 23 upward, thus injecting the liquid from 'A'. Plugs 28 delay injection as they provide an impediment to the flow of the water from 'D' through the holes in the bottom of 25 onto the bottom of 23. Thus, most of P_H can be removed before a significant amount of water is displaced from 'D' through 25. The geometry of 'j' can be varied by using different thickness spacer 29. Also plugs 24 and 7^* from mode J can be placed in lieu of 26 and 7^{**} thus resulting in a simpler geometry as in mode J. Mode L can be operated without the plugs 28. With the plugs, piston 3^* will start its motion when P_H drops to some value between $P_C / 1.71$ and $P_C / 3.77$.

There are various ways for controlling the injection process. They are discussed in Section IV together with examples of the predicted performance of the various modes of operation.

III. FORMULATION OF INJECTOR OPERATION

In this section, the operation of the injector in its various modes of operation is formulated. The following assumptions are made:

a) the liquid is considered incompressible.
b) the gas flow is isentropic.
c) the friction forces are negligible.
d) the liquid flow is considered steady, non-viscous and one dimensional.

Assumption 'a' simplifies the formulation a great deal and is justified considering the type of liquids and pressure range under consideration. Assumption 'b' introduces small errors in long injection processes. These errors can only be determined experimentally. Assumption 'c' is better for the higher pressures; its validity has to be determined experimentally. Assumption 'd' simplifies the solution and is justified based on the operating conditions considered. An estimated discharge coefficient C_D is introduced in order to account for assumption 'd'. The uncertainties in C_D mask those of assumptions 'a', 'b', and 'c'. Reasonable deviations from the above assumptions were simulated in the equations, and the solutions indicated less than 5% deviation in injector performance. Therefore, for the purpose of predicting the injector performance, the above assumptions are justifiable.

A. <u>Equations:</u>*

Balance of forces on the piston:

$$P_{AU} A_{AU} + P_C A_0 = P_L A_I + P_H A_H + M_P \frac{dU_P}{dt} \qquad (1)$$

Mass continuity of the liquid during injection:

$$U_P A_I = U_J A_T \qquad \text{for modes K, J} \qquad (2)$$
$$U_P (A_I + A_T) = U_J A_T \qquad \text{for mode L}$$

Steady Bernoulli Equations for the liquid flow:

$$P_L - P_C = \frac{\frac{1}{2} \rho_L U_J^2}{C_D^2} \qquad (3)$$

Isentropic gas equation of state in gas chambers:

$$\rho_* = C_* P_*^{\frac{1}{\gamma}} \qquad (4a)$$

$$C_* = \frac{\bar{M} P_{**}^{\frac{\gamma-1}{\gamma}}}{R\, T_{**}} \qquad (4b)$$

where $*$ stands for H, AU, C (corresponding to gas chambers C, B, and T in Fig. 1) and $**$ stands for HO, AUO, S respectively.

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*Symbols defined in Nomenclature, page 23.

Mass balance in gas chambers:

$$\frac{dm_*}{dt} = \frac{d\rho_*}{dt} V_* + \rho_* \frac{dV_*}{dt} \tag{5}$$

Gas chambers volume change in terms of piston velocity:

$$\frac{dV_H}{dt} = -A_H U_P \tag{6a}$$

$$\frac{dV_{AU}}{dt} = A_{AU} U_P \tag{6b}$$

$$\frac{dV_C}{dt} = (A_0 - A_I) U_P \tag{6c}$$

Mass change in gas chambers:

$$\frac{dm_H}{dt} = \gamma^{\frac{1}{2}} \left(\frac{2}{1+\gamma}\right)^{\frac{\gamma+1}{2(\gamma-1)}} C_H^{\frac{1}{2}} P_H^{\frac{\gamma+1}{2\gamma}} A_{TH} \qquad \text{when choked} \tag{7a}$$

$$\frac{dm_H}{dt} = -C_H^{\frac{1}{2}} \left(\frac{2\gamma}{\gamma-1}\right)^{\frac{1}{2}} P_A^{\frac{\gamma+1}{2\gamma}} \left[\left(\frac{P_H}{P_A}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]^{\frac{1}{2}} A_{TH} \qquad \text{when not choked} \tag{7b}$$

$$\frac{dm_{AU}}{dt} = C_{AU}^{\frac{1}{2}} \left(\frac{2\gamma}{\gamma-1}\right)^{\frac{1}{2}} P_{AU}^{\frac{\gamma+1}{2\gamma}} \left[\left(\frac{P_{AU0}}{P_{AU}}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]^{\frac{1}{2}} A_{TAU} \tag{7c}$$

$$\frac{dm_C}{dt} = C_C^{\frac{1}{2}} \left(\frac{2\gamma}{\gamma-1}\right)^{\frac{1}{2}} P_C^{\frac{\gamma+1}{2\gamma}} \left[\left(\frac{P_S}{P_C}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]^{\frac{1}{2}} A_S \tag{7d}$$

Equations (1) to (7) can be reduced to a system of 5 ordinary differential equations (ODE) with the general form:

$$\frac{dP_H}{dt} = f_1 (P_H, V_H, U_P) \tag{8a}$$

$$\frac{dP_C}{dt} = f_2 (P_C, V_H, U_P) \tag{8b}$$

$$\frac{dV_H}{dt} = f_3 (U_P) \tag{8c}$$

$$\frac{dP_{AU}}{dt} = f_4 (P_{AU}, V_H, U_P) \tag{8d}$$

$$\frac{dU_P}{dt} = f_5 (P_C, P_H, P_{AU}, U_P) \tag{8e}$$

For conciseness, the exact forms of Eqs.(8) are not given here. Their forms can be determined from the Program INJFLOW given in Appendix A.

The initial conditions for Eqs.(8) are:

$$P_H(t=0) = P_{H0} \qquad P_{AU}(t=0) = P_{AU0} \qquad P_C(t=0) = P_S \tag{9}$$

$$V_H(t=0) = V_{H0} \qquad U_P(t=0) = 0$$

Notes:

1) Equation (8b) holds for the case when the test chamber is interconnected to a large capacity pressure reservoir P_S.

2) A different mode of operation results when P_C is prescribed in a given manner. An exponential pressure rise is considered (simulating a gun cycle after ignition, or injection during a rapid pressurization of the test chamber to a pressure P_S) in the form:

$$P_C = P_S\left(1 - e^{-a_{exp}t}\right) \tag{10}$$

In this case Eq. (9) replaces Eq. (8b) and Eqs. (8) are reduced to 4 ODE's .

Condition for injector initiation (injector opening) will now be described:

Note that Eq. (1) is valid only when the hold pressure has vented to a point when the test chamber no longer exerts a restraining force on the face of the piston. It is only then that the piston may start its motion, thus initiating the injection. The piston however may be blocked from movement due to excess liquid pressure build up behind the plugs (28 in Figure 1c) in Mode L or behind the pilot shaft (10 in Figure 1a) in Mode K. As the hold pressure is vented further, the plugs and/or the pilot shaft recede thus triggering the injection. In order to account for the various modes of operation, Eqs. (8) have to be solved with respect to the various modes of injector opening (ie.,injector initiation at $t=t_{OP}$). Therefore Eqs. (8) are subjected to the following constraints:

$$\frac{dU_P}{dt}(t<t_{OP}) = 0 \tag{11a}$$

$$P_L(t<t_{OP}) = P_C \qquad P_H = P_{HOP} \text{ when } t = t_{OP} \tag{11b}$$

$$P_{HOP} \le \frac{P_{AU}A_{AU} + P_C(A_0 - A_I)}{A_H} \qquad \text{except when opening mode of pilot shaft or plugs} \tag{11c}$$

$$P_{HOP} \le \frac{P_C A_0 + P_{AU}A_{AU}}{2.25A_I + A_H} \qquad \text{for Mode K with pilot shaft} \tag{11d}$$

$$P_{HOP} \ge P_C\left[\frac{A_{MS}(A_0 + A_T) - (A_I + A_T - A_{PS})(A_I + A_T - A_{MS})}{A_{MS}A_H}\right] \quad \text{for Mode L with plugs} \tag{11e}$$

B. <u>Solution:</u>

A fourth order Runge-Kutta method is used to solve Eqs. (8). The equations are stiff ODE's and extensive logic is used for controlling the time steps in order to minimize their number and yet assuring solution convergence and accuracy. The ODE's are made less stiff if the piston inertia term in Eq. (1) is neglected which renders Eq. (8e) algebraic. Therefore, the value of the inertia term is constantly checked during the solution and it is neglected if its magnitude is much smaller with respect to the other terms in Eq. (1) (or their equivalent in Eq. (8d)). If the inertia term is neglected then only 4 ODE's are solved (or 3 ODE's if Eq. (10) applies). As Eq. (11) indicates, only 1 ODE is solved for $t < t_{OP}$. For the simulation of the injector operation, a Microway FORTRAN program INJFLOW was written (APPENDIX A) and run on a 386 based PC-AT.

Input:

The various modes of operation of the injector and its operating parameters are interactively input at the terminal according to the flow chart given in APPENDIX B.

Output:

The various injector performance variables are displayed on the monitor in a tabular form during the solution execution. They are also simultaneously stored in ASCII files on the system disk. The files automatically assume coded names in accordance with the input for the runs. All file names are eight characters long, plus a three digit suffix. The first character declares the type of injection being modeled. It is either 'K' for a circular injection (mode K) or 'L' or 'J' for an annular injection (mode L or J respectively). The second character is either 'P' for the preset test chamber pressure mode (Eq. 9), or 'E' for the exponential test chamber pressure mode (Eq. 10). The third through fifth characters are either the hold discharge orifice diameter in thousandths of an inch, or are 'HHH' if constant hold pressure is kept. The sixth character has different meanings depending on whether the injection was circular or annular. If circular, it is either 'S' for pilot shaft (10) present, 'N' for no pilot shaft present, or 'A' for an arbitrary opening hold pressure (a shaft is present). If annular, it is 'P' for using plugs (28), 'N' for not using plugs, or 'A' for an arbitrary opening hold pressure (plugs are present). The seventh character gives the value for C_D in tenths, and reads '0' if $C_D = 1$. The eighth character gives the liquid injected. It is 'P' for propellant (LP), 'W' for water, or 'M' for a miscellaneous liquid. The three digits in the suffix give the injection orifice diameter in thousandths of an inch for circular injections, or the injection orifice diameter minus an inch for annular injections (outer diameter for mode J, inner diameter for mode L).

IV. INJECTOR PERFORMANCE

In this section, the predicted performance of the injector is given for selected operating conditions. It is not intended here to cover the entire performance envelope of the injector, but rather to demonstrate the trends of the performance as calculated based on the formulation of Section III. This will cue the user on the feasibility of desired injection velocity profiles. The theoretical predictions are given in Figures 3 to 8. Actual test results and comparison to theory are given in Figure 9. In all Figures, the file name corresponding to the operational parameters used are given at the top (e.g., KP200N9P.020 in Fig.3); thus, the parameters can be deciphered as explained in Section III.

A. Predicted Performance

In Figs. 3-8, the hold volume is set such that the volume injected is approximately 45 cc. Also the initial hold pressures are set such that they are only slightly above the minimum required to prevent injection. The augment pressure is always applied only after injection initiation. In all cases LGP1846 is the liquid injected. (Lighter liquids will result in higher injection velocities.)

The injector performances for mode K (circular orifice) are given in Figs. 3-5 for the range of ambient pressures which will be tested in the SRF. In each Figure, injection velocities were calculated for cases with and without augment pressure. (Note that the augment pressure should always be lower than the ambient pressure; otherwise Part 4 will unseat from Part 2. For identification of Parts and Volumes, see Fig. 1.) Figures 3 and 4 cover extremes in the injector orifice size (small and large, respectively) when the hold discharge orifice, A_{TH}, is the largest possible size. A large A_{TH} results in faster rates of P_H decrease and P_L increase. For the small injection orifice (Fig. 3), the injector piston (Part 3) moves slowly enough such that P_H drops to atmospheric value very early in the injection period which results in steady, high injection velocities. Also, the augment volume ('B') expands at a slow rate such that P_{AU} is sustained in its initial set value despite the small inlet area A_{TAU}. In contrast, for the larger injection orifice (Fig. 4), the injection piston moves faster which recompresses the gas in 'C' such that P_H never drops to atmospheric value during the injection period. This results in an accelerating injection velocity during injection and the top injection velocity is smaller than the one achieved with the smaller injector orifice for the same operating pressures. Notably, P_{AU} drops as the gas supply through A_{TAU} cannot keep up with the rapidly expanding 'B'. As can be seen from Fig. 4, with the proper level of P_{AU}, the injection velocity profile can be made flatter. In Fig. 5, a medium sized injection orifice is used with a small A_{TH}. This results in a long duration, steady albeit low injection velocity. The velocity stabilizes early as the volume 'C' decreases at a rate which compensates exactly for the discharge of gas from it through the small A_{TH}. When augment pressure is used, the initial piston velocity is high but settles down as both P_{AU} and P_H stabilize.

Note that Figs. 3-5 deal with injector opening mode of no pilot shaft (Part 10). As seen in the detailed inset of Fig. 5, when P_{AU} is applied, P_H is compressed to values above its initial value which would cause Part 10 in a pilot shaft mode to seal the injection orifice and thus terminate the injection prematurely. In Figs. 4 and 5, the inset details are for cases when P_{H0} is set well above the value required to prevent injection. As P_{H0} is discharged, injection starts and is then boosted further by the application of P_{AU}. In Fig. 4, the injection velocity profiles could have been made flatter had a pilot shaft opening mode been used. This is because in this mode the injection velocity starts at a value above 100 m/s.

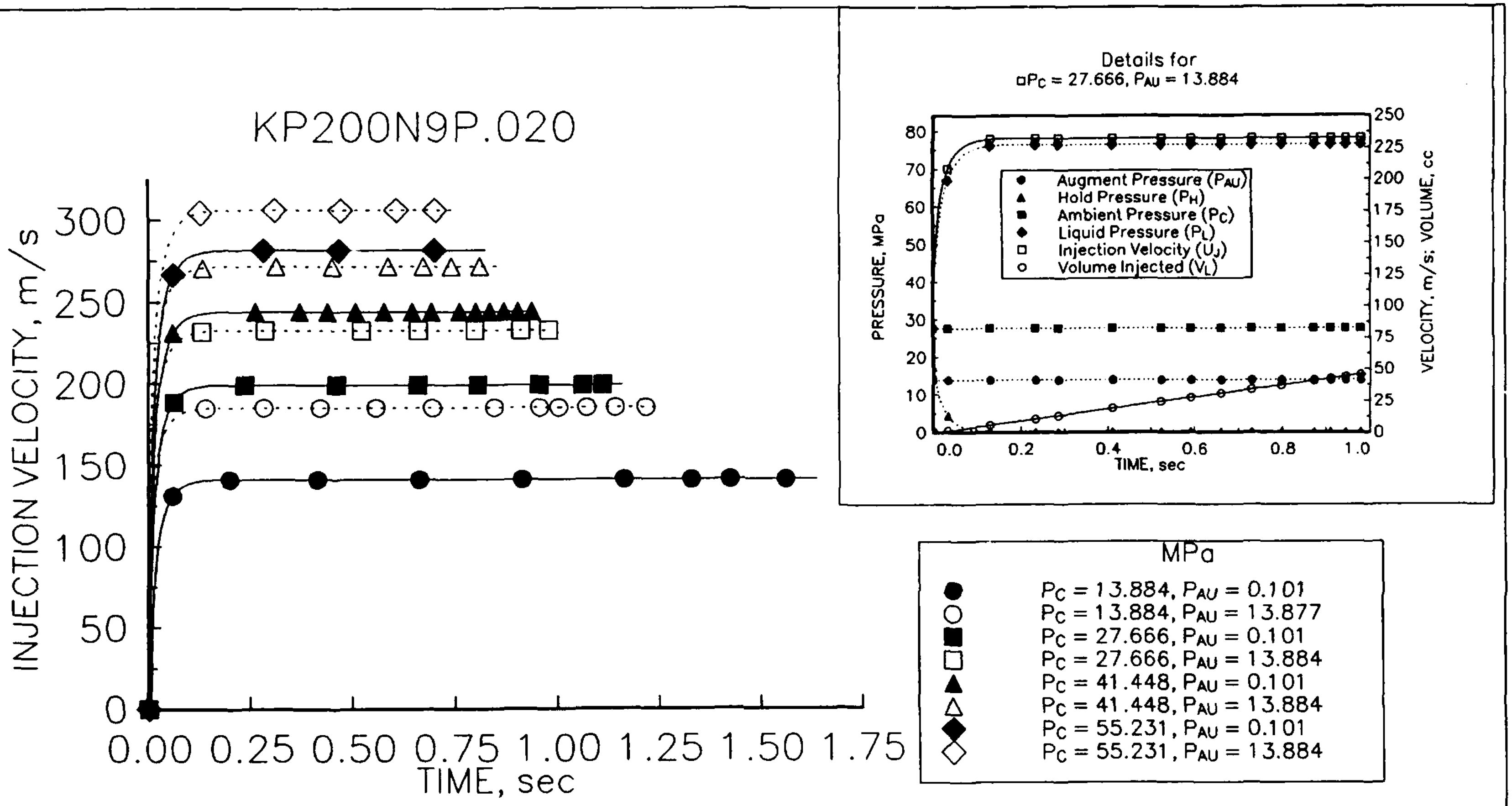

Fig.3 **Steady maximum injection velocity is obtained with thin circular jets early in the injection period.**

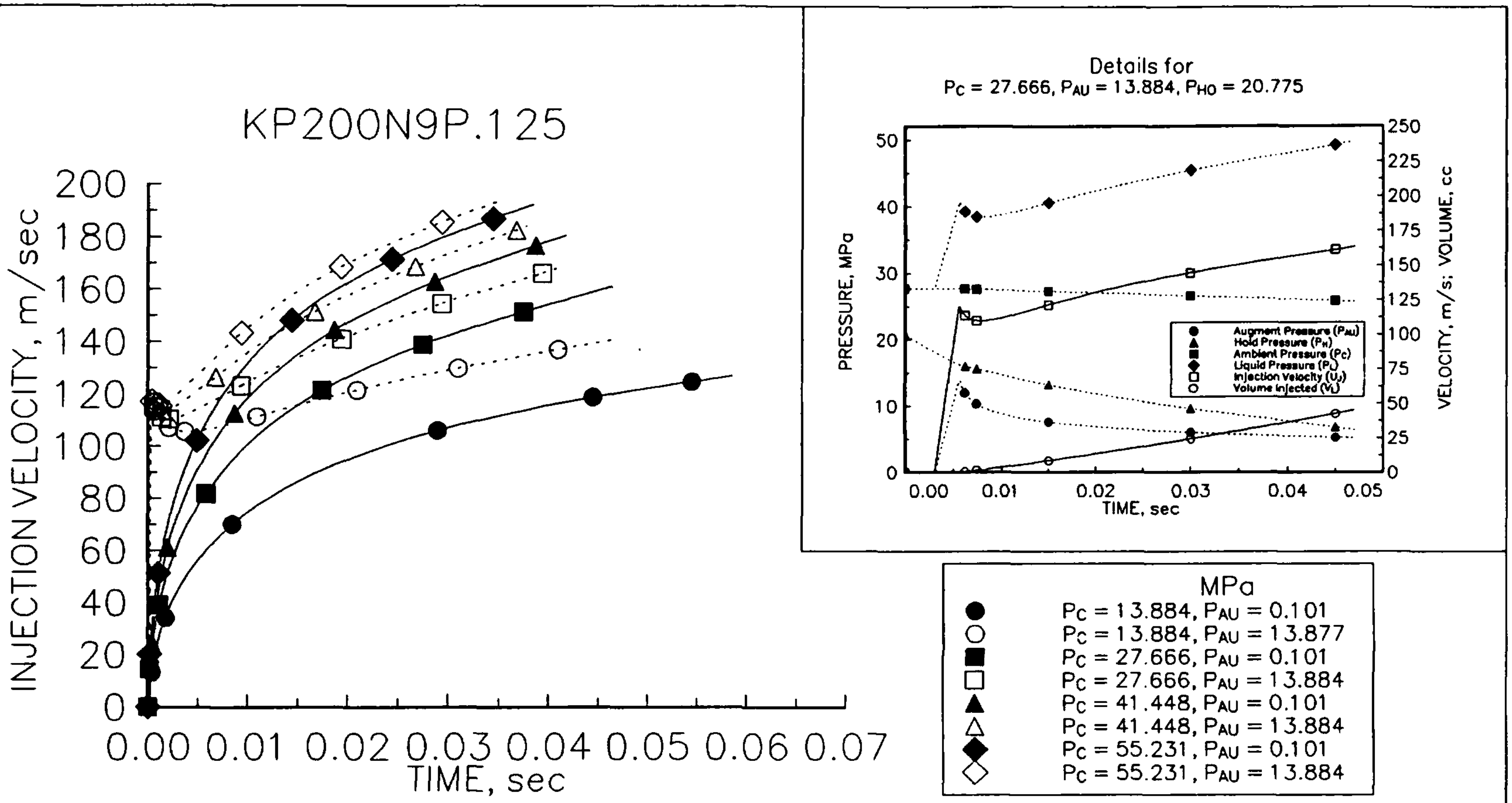

Fig.4 Injection velocities of thick circular jets approach top velocity only toward the end of the injection period.

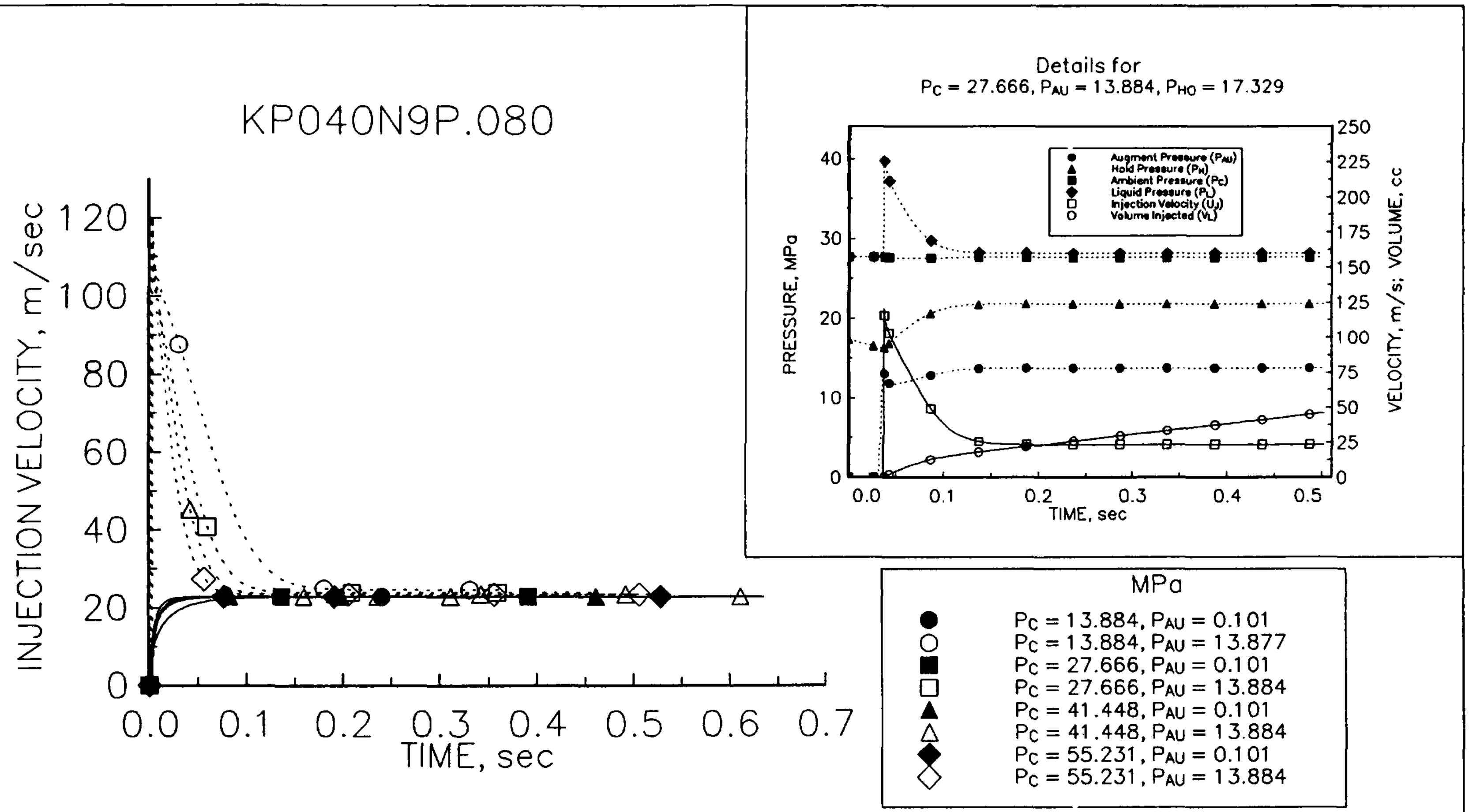

Fig. 5 Long duration steady injection of thick jets can be achieved by throttling down the hold volume discharge.

The cases covered in cases Figs. 3-5 are examples which show the trends in expected performance with respect to variables such as the injection orifice size, pressures on the injector piston, and the hold discharge orifice. As shown, for small injection orifices, the injection duration is long and the hold volume 'C' changes slowly. For such a case it is possible to hold P_H constant at a preset value by means of a regulator. Injection may be initiated by the application of P_{AU} which is the case shown in Fig. 6. Injection can also be initiated by increasing the ambient pressure P_C as shown in Fig. 7 for an exponential ambient pressure rise. In Fig. 7, P_{AU} is atmospheric and only a small P_{H0} is required. Obviously, variations on these themes may be used in order to achieve any desired injection profile.

As Figs. 3-8 indicate, it is reasonable to expect injection velocities from 200 m/s to over 300 m/s for circular jets of LGP1846 which range in diameter from 3.2 mm (0.125 inch) to below 0.5 mm (0.020 inch) respectively. For the thickest jets, the top injection velocity is achieved only toward the end of the injection period. The injection velocities attainable with the annular jets are lower than with the circular jets. This is because the annular jets have larger cross sectional areas which require higher injector piston velocities in order to achieve the same high injection velocities. This in turn recompresses the gas in the hold volume, thus impeding injection.

In mode L, shown in Fig. 8, the opening injector pressure P_{HOP} can be controlled by the use of plugs (Part 28). For example, for P_C = 27.7 MPa, without the use of plugs, a top velocity of 25 m/s is obtained with an annular jet 1 mm (0.040 inch) thick and 25.4 mm (1.0 inch) ID. For the same jet, with the use of the plugs, injection velocity starts at 150 m/s and drops to 90 m/s during the 5 ms injection period. A set of newly designed plugs are expected to open at P_{HOP} = 1.48 MPa which will result in 190 to 175 m/s, over a 3 ms injection. Note, that P_C drops because the ambient gas is not provided quickly enough to allow for the expansion of 'A' as the injector piston withdraws from the bottom of 'A'. The performance of Mode J injection which lacks the plugs is rather similar to the performance of Mode L without the plugs. The maximum injection velocity is limited by the minimum P_{H0} which is required to hold the piston against P_C, and by the maximum available discharge area A_{TH}. If the injector is operated as a true RLPG injector, i.e., with minimal P_{H0} under exponentially increasing P_C, then injection velocities in the range of 300 m/s are achievable even with 3 mm (0.120 inch) thick - 25.4 mm (1.0 inch) ID annular jets. Obviously, the injection durations will be very short which means that P_C has to be applied very rapidly. This can be achieved only by employing a high output gas generator in lieu of the present nitrogen gas supply. The injector performance for thick jets can be improved significantly if it is operated with helium in lieu of nitrogen but the operation will be less practical.

B. Experimental Performance

The predicted performance of the injector was validated in a series of tests. The test shown in Fig. 9 is typical for mode K (circular) injection with the use of the pilot shaft (Part 10). P_C was preset at 28 MPa and P_{H0} was set at 14.5 MPa (time A). Experimentally, the pilot shaft retracted from the injection port at about 9.5 MPa (time B) thus opening the injector and initiating the injection. As explained in Section 2, from time A to B, transducer 17 measures P_H directly and thus its output is the same as transducer 'p' (Fig. 1). During the injection (time B to C), 'p' continues the measurement of P_H while transducer 17 measures P_L via shaft 10. The output of 17 during injection has to be multiplied by a 2.25 area factor; hence the new scale for P_L at time B. The experimental V_L curve was calculated from the magnetic sensor (Part 16) data. (About 78 cc of water was injected.) P_C dropped significantly during the injection due to the expansion of 'A'. (The gas supply level was too low in the experiment.)

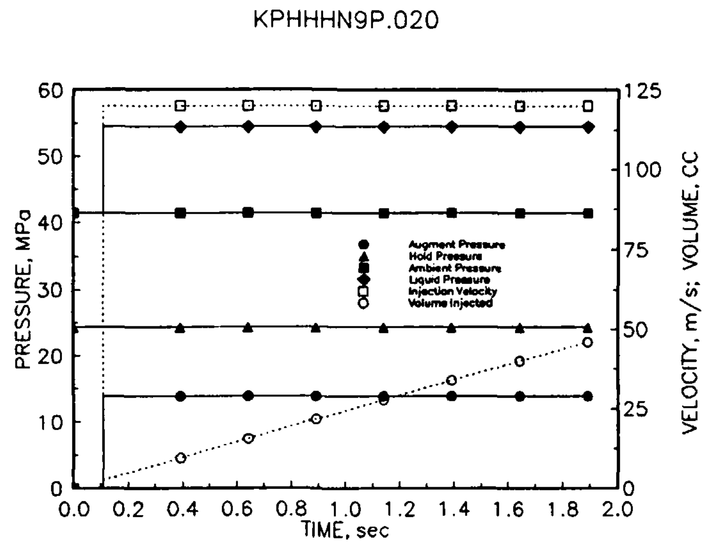

Fig. 6 Initiation of injection by application of augment pressure while maintaining the hold pressure at a preset value.

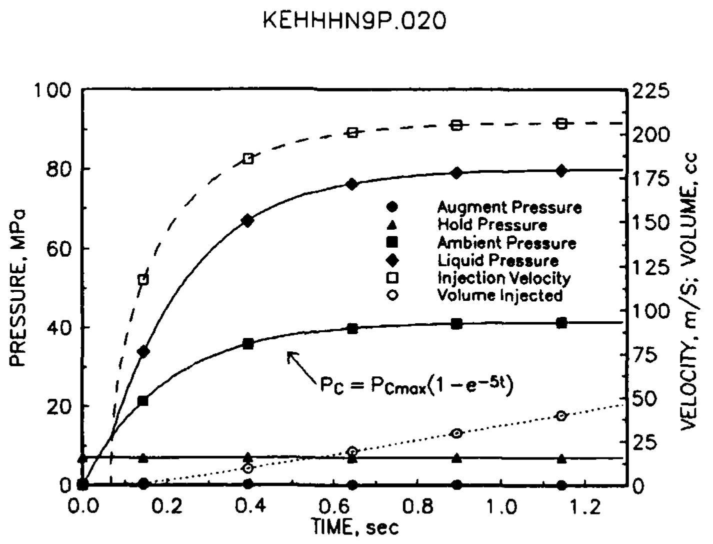

Fig. 7 Initiation of injection by pressurization of the test chamber while maintaining the hold pressure.

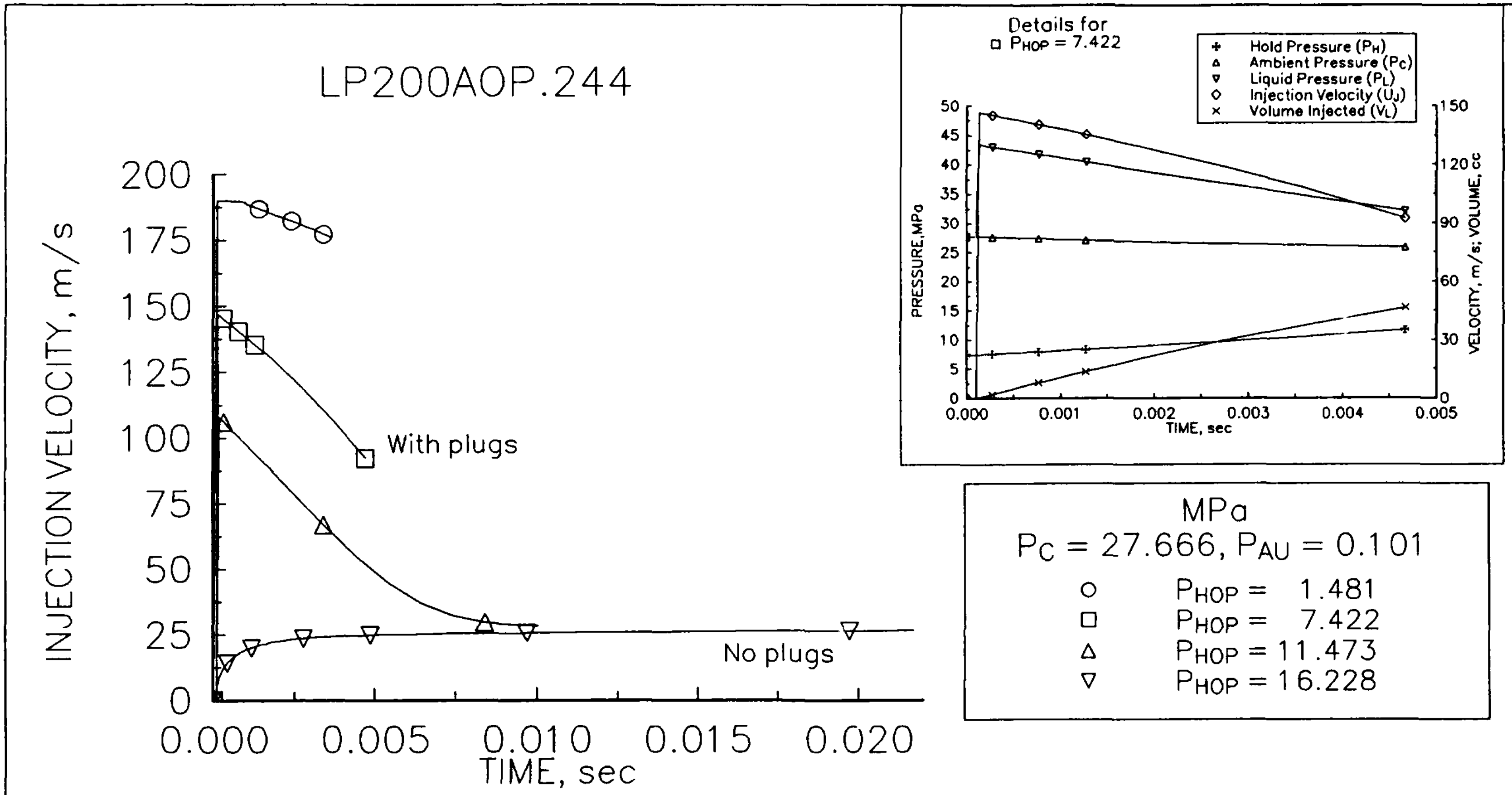

Fig. 8 Annular jet performance is very dependent on the hold pressure at the initiation of the injection.

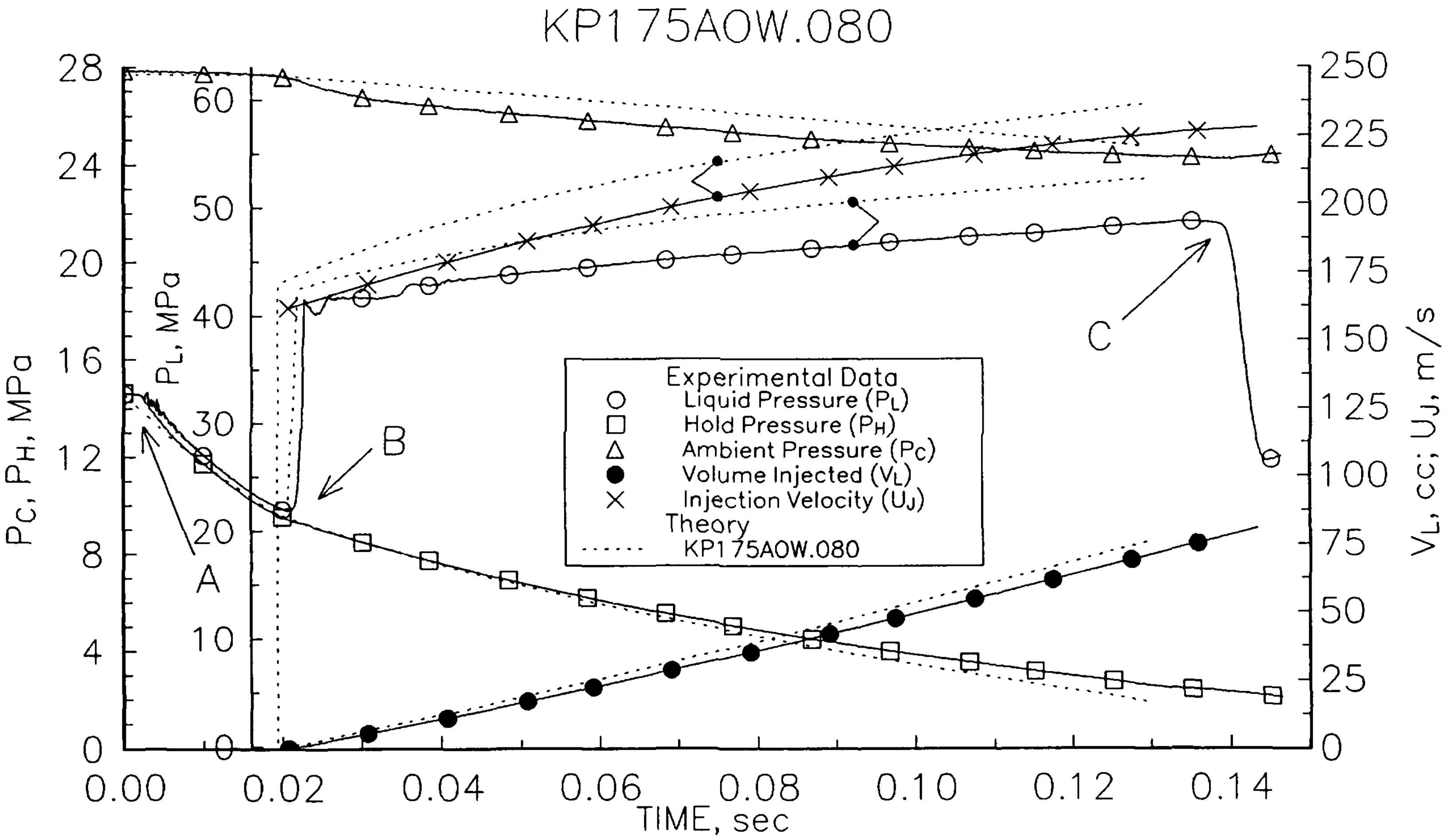

Fig. 9 Comparison between theoretical analysis and experimental data on the operation of the injector.

Experimentally, the most precise data are for P_H, P_C, and the times A, B, and C. The least precise data are for P_L. For validation of the theoretical model, the code INJFLOW was run with the experimental opening pressure of the injector (P_{HOP} at time B) as an input. As evidenced from Fig. 9, the agreement between the experiment and theory is quite good. As expected, the model predicted better performance when a discharge coefficient of one was used and no losses were taken into account.

V. CONCLUDING REMARKS

1. Based on model predictions and supported by experiments, the injector performance is adequate for the studies of RLPG type injection processes. With circular geometries, the full range of RLPG jet velocities can be researched with mass flow rates up to 3 kg/s. With annular geometries approximating a 30-mm RLPG, mass flow rates up to 10 kg/s may be obtained but with attendant injection velocities below 200 m/s. With circular jets up to 92 cc of liquid can be injected, while with annular jets injection volume is limited to 45 cc.

2. Operation with the thinner (2 mm (0.080 inch) in diameter) circular jets offers long injection durations with steady injection velocities which are needed for statistical analysis of particle sizing data, generated by Phase Doppler Particle Analyzer measurements of the spray.

3. The use of the pilot shaft opening mode is attractive for studies of basic circular LGP jet combustion. This is because the pilot shaft protects the liquid propellant in the injector from being ignited by the hot ambient gas prior to injection. Combustion tests with LGP1845 circular jets below 2 mm in diameter have been conducted recently[4].

4. Thick circular jets and particularly annular jets will be studied primarily in non-combusting environment using high speed cinematography and flash X-ray radiography.

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4. Birk, A. and Bliesener, G., "Topics on Liquid Propellant Combustion in Closed Chambers", 27th JANNAF Combustion Meeting, Cheyenne, Wyoming, November 1990.

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NOMENCLATURE

A_{AU} - Augment action area
a_{exp} - Exponential ambient pressure rise
A_H - Hold action area
A_I - Inside piston area
A_{MS} - Effective plugs (part 28) cross section area
A_O - Outside piston area
A_{PS} - Cross section area of pedestal (part 25)
A_S - Effective test chamber gas supply inlet area
A_{TAU} - Augment volume inlet area
A_T - Injection port area
A_{TH} - Hold volume discharge area
C_D - Discharge coefficient
M - Mass
M_P - Piston mass
M - Molecular weight
P - Pressure
R - Universal gas constant
t - Time
T - Temperature
U_J - Injection velocity
U_P - Piston velocity
V - Volume
V_L - Liquid volume injected
γ - Specific heat ratio
ρ_L - Liquid density

SUBSCRIPTS

A - Atmospheric
AU - Augment
AUO - Augment at time zero
C - Test chamber (ambient conditions)
H - Hold
HO - Hold at time zero
HOP - Hold opening pressure
L - Liquid
S - Supply reservoir

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APPENDIX A:

INTERACTIVE COMPUTER CODE INJFLOW

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APPENDIX A: INTERACTIVE COMPUTER CODE INJFLOW

```
      program INJFLOW

      integer atc,athc,athx,atx,cdx,ii,inj,k,kk,ll,n,nmo,nout,runge,wp
      parameter (n=5,nout=6)
      logical aa,ffp,ffpp,init,paps,plug,ppa,ppcm,ppns,ptrue,upno,
     1 uptrue,uptrue1
      character name*12,part2*3,part4a*6,part3*1,part1a*1,part1b*2,
     1    part5*1,part4b*3,part2a*1,part3a*4
      double precision aamp,aaug,aexp,ah,ahmp,ai,aih,aiot,amsh,ao,aoio,
     1    ar,as,asa,at,ath,ath0,atth,at0,cd,co1,co2,c1,f(n),gam,gamah,
     2    gamaug,gamp,gamt,gam1,gmo,gmoo,h,hh,hhv,h0,h1,mp,mw,pa,pac,
     3    pac1,pag,paug,pc,ph,phi(n),phinn,phoop,phop,pl,plo,ps,rho,rol,
     4    rol1,savey(n),tij,ts,uj,vaoo,vatth,vaug,vcho,vco,vh,x,y(n)

c     variables common to main program and fcn subroutine
      common /alpha/aamp,aexp,ah,ahmp,aoio,co1,co2,c1,gamah,gamaug,
     1    gamp,gamt,gam1,gmo,gmoo,pa,pag,paps,paug,ppcm,ps,rol,upno,
     2    vaoo,vcho

c     numeric variables common to main program and out subroutine
      common /beta/atth,atx,init,inj,pac,vatth,wp

c     variables common to main program, fcn and out subroutines
      common /delta/aa,aiot,rol1,uptrue1

c________________________________________________________________________
```

aaug = A_{AU}
aexp = A_{EXP}
ah = A_H
ai = A_I
ams = A_{MS}
ao = A_0
aps = A_{PS}
as = A_S
asa = A_{TAU}
at = A_T
ath = A_{TH}
cd = C_D

dvl = V_L
f(i) = $\frac{dy(i)}{dt}$
gam = γ
h = Δt
mp = M_P
mw = $\bar{M}$
pa = P_A
paug = P_{AU}
pc = P_C
ph = P_H
phoop = P_{HOP}
pl = P_L

ps = P_S
rho = ρ_L
ts = T_S
uj = U_J
vc = V_C
vh = V_H
x = t
y(1) = P_H
y(2) = P_C
y(3) = V_H
y(4) = P_{AU}
y(5) = U_P

```
c________________________________________________________________________
c     Prompt Area
c     Liquid Choice

    4 print*,'Please choose the liquid to be injected.'
      print 101, ' 1) LP ', ' 2) Water ', ' 3) Miscellaneous'
      read*,kk
      if(kk.eq.1) then
         rho = 1.46
         part5 = 'P'
      elseif(kk.eq.2) then
         rho = 1.
         part5 = 'W'
      elseif(kk.eq.3) then
         part5 = 'M'
         print30, ' Enter the density of the liquid (g/cc).'
         read*,rho
      else
         goto 4
      endif

c     Chamber Pressure Mode
```

```
      print*,'Please enter chamber pressure mode.'
      print 10,' 1)  Preset.',' 2)  Exponential rise.'
      read*,kk
      if(kk.eq.1) ppcm = .false.
      if(kk.eq.2) ppcm = .true.
      if(ppcm) then
        print*,'Please enter exponent.'
        read*, aexp
      endif

c     Injection Mode

      print*,'Please enter the injection mode.'
      print 10,' 1)  Hold discharge.',' 2)  Constant hold pressure.'
      read*,kk
      if(kk.eq.2) paps = .true.
      if(kk.eq.1) paps = .false.

c     Injection Type

      print*,'Please pick the number corresponding to the type of injec
     1tion to be modeled.'
      print 101,' 1)  Circular injection - Mode K',' 2)  Annular injec
     1tion - Mode L',' 3)  Annular injection - Mode J'
 10   format(1x,a/a)
101   format(1x,a/a/a)
      read*,inj
      if(inj.eq.1) ffp = .false.
      if(inj.eq.2) ffp = .true.
      if(inj.eq.3) ffpp = .true.

c     CD

      print 30, 'Please enter estimated value for CD.'
      read*,cd
      cdx = cd*10.
      write(unit = part3, fmt = '(i1)') cdx
      if(cdx.eq.10) part3 = 'O'

c     Opening Mode For Mode K Injection

  3   if(.not.(ffp.or.ffpp)) then
         print*,'Please enter the mode of opening.'
         print 101,' 1)  Pilot shaft',' 2)  No pilot shaft',' 3)  Arb
     1itrary (only if hold discharge)'
         read*,kk
         if(kk.eq.1) then
            ppns = .false.
            part2a = 'S'
         else
            ppns = .true.
            part2a = 'N'
         endif
         if(kk.eq.3) then
            if(paps)goto3
            print*,'Please enter opening hold pressure (psig).'
            read*, phoop
            ppa = .true.
            part2a = 'A'
         endif
      endif

c     Injection Orifice Diameter For Mode K Injection

  7   if(.not.(ffp.or.ffpp)) then
         print*,'Please choose the size of the injection orifice (inche
     1s).'
         print 14,' 1) .020',' 2) .040',' 3) .080',' 4) .125'
         read*,atc
         if(atc.eq.1) then
```

```
          at = .02
          part4a = part5//'.020'
        elseif(atc.eq.2) then
          at = .04
          part4a = part5//'.040'
        elseif(atc.eq.3) then
          at = .08
          part4a = part5//'.080'
        elseif(atc.eq.4) then
          at = .125
          part4a = part5//'.125'
        else
          goto 7
        endif
      endif
14    format (1x,a/a/a/a)
 8    format (1x,a/a/a/a/a)

c     Opening Mode For Mode L Injection

      if(ffp.or.ffpp) then
        if(ffp) then
          print*,'Please pick the number corresponding to the mode of
     1 injection to be modeled.'
          print 101,' 1)  With plugs.',' 2)  Without plugs.',' 3)
     1Arbitrary.'
          read*,wp
          if(wp.eq.3) then
            print*,'Please enter opening hold pressure (psig).'
            read*, phoop
            ppa = .true.
          endif
        endif

c     Injection Annular Orifice Diameter For Injection Modes J and L

19     if(ffp) print 30, 'Please enter inner annular diameter (between
     11.00 and 1.31 inches).'
       if(ffpp) print 30, 'Please enter outer annular diameter (between
     1 1.00 and 1.308 inches).'
       read 26,at
       if(at.lt.1.00.or.at.gt.1.308) goto 19
       atx = at*1000
       atx = atx-1000
       write(part4b, fmt = '(i3.3)') atx
       if(wp.eq.1) plug = .true.
       if(wp.eq.2) plug = .false.
       part3a = 'N'//part3//part5//'.'
       if(plug) part3a = 'P'//part3//part5//'.'
       if(ppa) part3a = 'A'//part3//part5//'.'
      endif
      at0 = at
c     Reservoir Supply Temperature

      print 30, 'Please enter reservoir supply temperature in Celsius.'
      read*, ts
      ts = ts+273.
      pac = pa/14.7

c     Constant Hold

      if(paps) then
        ath = 0.0
        part2 = 'HHH'
        goto 11
      endif
c     Hold Discharge Orifice Size

 9    print 30, 'Please choose the size of the discharge orifice (inche
     1s).'
      print 8, ' 1) .020',' 2) 1/32',' 3) 1/16',' 4) wide open',
```

```
     1 '  5) miscellaneous'
      read*,athc
      if(athc.eq.1) then
         ath = .02
         part2 = '020'
      elseif(athc.eq.2) then
         ath = .03125
         part2 = '031'
      elseif(athc.eq.3) then
         ath = .0625
         part2 = '062'
      elseif(athc.eq.4) then
         ath = .200
         part2 = '200'
      elseif(athc.eq.5) then
         print 30, 'Please input discharge orifice size (inches).'
         read 26,ath
         athx = ath*1000
         write(part2, fmt = '(i3.3)') athx
      else
         goto 9
 25   endif
      ath0 = ath
 11   at = at0
      ath = ath0
      init = .true.

c     Maximum Test Chamber Pressure

 5    print 30, 'Please enter chamber pressure in psi.'
      read*, ps

c     Hold Pressure

      print 30, 'Please enter hold pressure in psi.'
      read*, ph

c     Augment Pressure
      if (ppcm) paug = 0.
      if(.not.ppcm) then
 6     print 30, 'Please enter augment pressure in psi.'
       read*, paug
       if(paug.ge.ps) then
         print*
         print*,'Caution, augment pressure too high.'
         goto 6
       endif
      endif
 23   format(1x,a3)
 26   format(f5.3)
 30   format(1x,a)
 31   if(.not.(ffp.or.ffpp)) then
         part1a = 'KP'
         if(ppcm) part1a = 'KE'
         name = part1a//part2//part2a//part3//part4a
      else
         part1b = 'LP'
         if(ppcm) part1b = 'LE'
         if(ffpp) part1b = 'JP'
         if(ffpp.and.ppcm) part1b = 'JE'
         name = part1b//part2//part3a//part4b
      endif

c     Hold Volume

 33   print*,'Please enter the hold volume (cc).'
      print 14,' 1) 231.25 (max)',' 2) 129.125',' 3) 95.08',' 4) Arb
     1itrary'
      read*,kk
      if(kk.eq.1)then
         vh = 231.25
```

```
      elseif(kk.eq.2)then
         vh = 129.125
      elseif(kk.eq.3)then
         vh = 95.08
      elseif(kk.eq.4)then
         print*, 'please enter volume'
         read*,vh
      else
         goto 33
      endif

c     conversion area

      data pa,vaug,aaug,asa,ah,gam,mw,h0,h1/1013000.0,1.37,16.67,0.0075
     1,39.1,1.4,28.0,1.d-6,5.d-4/
      pac1 = 14.7*pac
      ps = (ps+14.7)*pac
      ph = (ph+14.7)*pac
      paug =(paug+14.7)*pac
      phop = (phoop+14.7)*pac
      at = at*2.54
      at = 3.14159*(at/2.0)**2
      ath = ath*2.54
      ath = 3.14159*(ath/2.0)**2
      if(.not.(ffp.or.ffpp)) then
         ao = 40.53
         ai = 17.65
         vco = 1047.6
         mp = 2750.0
      else
         if(ffp) at = 8.68-at
         if(ffpp) at = at-5.067
         if(ffp) ao = 45.60 -at
         if(ffpp) ao = 40.53 - at
         if(ffp) ai = 22.72 - at
         if(ffpp) ai = 17.65 - at
         vco = 829.72
         mp = 3950.0
      endif
      data ams,aps,ar,as,uj,aa,init,ppa,ffp,ffpp,ppns/7.6,5.07,0.32,
     10.01,0.0,.false.,.true.,.false.,.false.,.false.,.true./
      pc = ps
      pl = pc

c     more variables defined

      gam1 = (gam+1.0)/2.0
      gmo = gam/(gam-1.0)
      gmoo = 1.0/gmo
      c1 = gam/(ph**(gmoo/2.0)*mw**0.5/156100.0)*ath
      co1 = sqrt(ps**gmoo*mw/ts/83140000.0)
      co2= sqrt(paug**gmoo*mw)/156100.
      pag = pa**(gam1/gam)
      gamp = gam**0.5/gam1**(gam1/(gam-1.0))
      gam1 = 1.0/gam1**gmo
      gmo = (2.0*gmo)**0.5
      aih =  (ai-ao)/ah
      aah = -aaug/ah
      co1 = gam*gmo/co1*as/aih
      co2 = gam*gmo/co2*asa/aah
      gamt = (3.0*gam-1.0)/2.0/gam
      aiot = ai/at
      if(ffp) aiot = (ai+at)/at
      atth = aiot*at/ah
      vatth = atth*vh
      rol = ai*rho/2.0/cd**2/mp*aiot**2
      rol1 = rol*mp/ai
      aoio = (ao-ai)/mp
      ahmp = ah/mp
      aamp = aaug/mp
      vcho = (vco-aih*vh)/aih
```

```
      vaoo = (vaug-aah*vh)/aah
      gamah = gam*ah
      gamaug = gam*aaug
      if(ffp) amsh = (ams*(ao+at)-(ai+at-aps)*(ai+at-ams))/ams/ah

c     initial values

      nmo = 4
      uptrue = .true.
      uptrue1 = .false.
      upno = .true.
      ll = 0
      phin = 0.0
      psin = 0.0
      upin = 0.0
      phinn = 1
      ii = 0
      kk = 0
      x = 0.0
      if(ppcm) pc = pac1
      y(1) = ph
      y(2) = pc
      y(3) = vh
      y(4) = paug
      y(5) = 0.0
      hh = y(5)
      hhv= y(3)
      h=h0*10.

      call out(x,y,k,name)
      init = .false.
 40    if(aa) goto 60
      k = runge(nmo,y,f,x,h)
      if(k.ne.1) goto 50

c     Calculations

      call fcn(x,y,f)
      goto 40
 50    if(upno) f(5) = (y(5)-hh)/h
      hh = y(5)
      if(uptrue1.and.abs(f(1))/phinn.gt.2) h = h/2.
      if(.not.paps)phinn = abs(f(1))
      if(hhv-y(3).gt.y(3)) h = h/10.
      hhv = y(3)
      if((.not.ffp.and.ppns).or.(ffp.and..not.plug)) then
         plo = y(1)+y(2)*aih+pac1*aah
         if(ppa) plo = y(1)-phop
         zzv = (y(1)-plo)/pac-14.7
         if(ppa) zzv = phop/pac-14.7
         if(paps) zzzv = -plo/aah/pac-14.7
      endif
      if(.not.ffp.and..not.ppns) then
         plo = y(1)-y(2)/2.25
         zzv = y(2)/2.25/pac-14.7
         if(paps) zzzv = -plo/aah/pac-14.7
      endif
      if(ffp.and.plug) then
         plo = y(1)-y(2)*amsh
         zzv = y(2)*amsh/pac-14.7
         if(paps.and..not.ppcm) zzzv = -(y(1)-y(2)*amsh)/aah/pac-14.7
      endif
      ll = ll+1
      ii = ii+1
      kk = kk+1
      if(y(1).lt.pa) then
         h=1.d-4
         y(1)=pa
      endif
      if(uptrue) uptrue1 = plo.lt.1e-20
      if(ppcm) goto 52
```

```
      if((uptrue.and.uptrue1).and.ll.eq.1) then
         print*,'Not enough hold pressure, should be greater than', zzv
         print*,'  Please reenter.'
         ll = 0
         goto 11
      endif
      if(paps.and..not.ppa) then
         plo = plo+paug*aah
         if(uptrue) uptrue1 = plo.lt.1e-20
      endif
      if((paps.and.uptrue).and.(.not.uptrue1.and.ll.ge.2)) then
         print*,'Not enough augment pressure, should be greater than',
     1 zzzv
         print*,'  Please reenter.'
         goto 11
      endif
52    if(uptrue.and.uptrue1) then
         h = h0
         print 34,'INJECTOR OPENS','INJECTOR OPENS'
         uptrue = .not.uptrue1
         tij = x
      endif
34    format(1x/17x,a14,18x,a14/)
      if(abs(f(5)).gt.1.e6.and.uptrue1) then
         upno = .false.
         nmo = n
         print*,'NOW INTEGRATING 5 EQUATIONS'
         h = h0
      else
         upno = .true.
         nmo = n-1
      endif
      if(y(5).gt.50.) h1 = 1.d-4
      if(y(5).gt.500.) h1 = 1.d-5
      if(ii.lt.10) goto 40
      ptrue = abs(f(1)).gt.phin/1.1
      if(ppcm) ptrue = abs(f(2)).gt.psin/1.1
      if(uptrue1) ptrue = abs(f(5)).ge.upin/1.1.and.abs(f(5)).lt.1.e6
      if(ptrue) h = h*2.
      if(h.gt.h1) h = h1
      phin = abs(f(1))
      upin = abs(f(5))
      psin = abs(f(2))
      ii = 0

c     Output

      call out(x,y,kk,name)
      goto 40
60    continue
      kk = kk+1
      call out(x,y,kk,name)
      print*,'Injection Time = ', x-tij
      print*,'Total number of steps = ', kk
      end

c     Runge-Kutta Method For Solving Differential Equations

      integer function runge(n,y,f,x,h)
      double precision y,f,x,h,phi,savey
      integer j,m,n
      dimension  phi(5),savey(5),y(5),f(5)
      data m/0/
      m = m+1
      goto (1,2,3,4,5),m
1     runge = 1
      return
2     do 22 j = 1,n
      savey(j) = y(j)
      phi(j) = f(j)
22    y(j) = savey(j)+0.5*h*f(j)
```

```
      x = x+0.5*h
      runge = 1
      return
 3    do 33 j = 1,n
      phi(j) = phi(j)+2.*f(j)
 33   y(j) = savey(j)+0.5*h*f(j)
      runge = 1
      return
 4    do 44 j = 1,n
      phi(j) = phi(j)+2.*f(j)
 44   y(j) = savey(j)+h*f(j)
      x = x+0.5*h
      runge = 1
      return
 5    do 55 j = 1,n
 55   y(j) = savey(j)+(phi(j)+f(j))*h/6.
      m = 0
      runge = 0
      return
      end

c     Differential Equations

      subroutine fcn(x,y,f)
      integer n
      parameter (n=5)
      double precision x,f(n),y(n),pth,plo,ff,vcc,gam1,gmo,gmoo,c1,pag,
     1   gamp,gamt,aiot,rol,rol1,aoio,ahmp,pa,ps,ah,co1,vcho,
     2   gamah,c11,vaoo,co2,paug,gamaug,aamp,ccc,aexp
      logical aa,uptrue1,upno,paps,ppcm
      common /alpha/aamp,aexp,ah,ahmp,aoio,co1,co2,c1,gamah,gamaug,
     1    gamp,gamt,gam1,gmo,gmoo,pa,pag,paps,paug,ppcm,ps,rol,upno,
     2    vaoo,vcho
      common /delta/aa,aiot,rol1,uptrue1
      if(upno) y(5) = sqrt((y(2)*aoio-y(1)*ahmp+y(4)*aamp)/rol)
      if(.not.uptrue1) y(5) = 0.0
      if(y(3).le. 27.)then
         aa =.true.
         y(5) = 0.0
         goto 80
      endif
      vcc = vcho +y(3)
      if(paps) then
         f(1) = 0.0
      else
         pth = y(1)*gam1
         ff = gamah/y(3)*y(1)*y(5)
         c11 = c1/y(3)
         if(pth.gt.pa) then
            f(1) = -gamp*c11*y(1)**gamt+ff
         else
            if(y(1).lt.pa) y(1) = pa
            ccc = (y(1)/pa)**gmoo-1.0
            f(1) = -c11*gmo*y(1)**gmoo*pag*sqrt(ccc)+ff
         endif
      endif
      if(uptrue1) then
         if(.not.ppcm) f(2) = co1*y(2)**gamt/vcc*((ps/y(2))**gmoo-1)**
     1  0.5+y(2)*gamah*y(5)/vcc
         if(ppcm) f(2) = aexp*ps*exp(-aexp*x)
         f(3) = -ah*y(5)
         vcc = vcc-vcho+vaoo
         f(4) = co2*y(4)**gamt/vcc*((paug/y(4))**gmoo-1)**0.5+y(4)*gama
     1ug*y(5)/vcc
         f(5) = y(2)*aoio-rol*y(5)**2.0-y(1)*ahmp+y(4)*aamp
      else
         f(2) = 0.0
         if(ppcm) f(2) = aexp*ps*exp(-aexp*x)
         f(3) = 0.0
         f(4) = 0.0
         f(5) = 0.0
```

```
      endif
80    return
      end


      subroutine out(x,y,kk,name)

      integer nout,n,kk,ll,inj,wp,atx
      parameter (nout=6,n=5)
      double precision y(n),x,pac,pl,uj,roll,aiot,atth,vatth,dvl
      logical aa,init,uptrue1
      character*12 name
      common /beta/atth,atx,init,inj,pac,vatth,wp
      common /delta/aa,aiot,roll,uptrue1

      if(aa) goto 500
      pl = y(2)+roll*y(5)**2
      uj = y(5)*aiot/100.
      ll = (kk+1)/10
      dvl = vatth-atth*y(3)
      if(init) then
         write(nout,fmt=70)
70        format(' Massflow equations program results',/1x)
         print 110,'#','TIME','AUGM','HOLD','HOLD','VOL','INJ','CHAMB'
     1,'LIQ','PIST'
         print 120,'PRESS','PRESS','VOL','INJ','VEL','PRESS','PRESS','V
     1EL'
         print*,'======================================================
     1========================='
         print 100,ll,x,y(4)/pac,y(1)/pac,y(3),dvl,uj,y(2)/pac,pl/p
     1ac,y(5)/100.
         open (2,file=name,recl=10,form='formatted')
         write(2,105)ll,x,y(4)*1.d-7,y(1)*1.d-7,y(3),dvl,uj,y(2)*1.d-7,
     1pl*1.d-7,y(5)/100.
       endif
       if(.not.init) then
         print 100,ll,x,y(4)/pac,y(1)/pac,y(3),dvl,uj,y(2)/pac,pl/pac,y
     1(5)/100.
         write(2,105)ll,x,y(4)*1.d-7,y(1)*1.d-7,y(3),dvl,uj,y(2)*1.d-7,
     1pl*1.d-7,y(5)/100.
       endif
100    format(1x,i4,1x,f7.5,1x,f7.2,1x,f8.3,3(1x,f7.3),2(1x,f8.2),1x,f6.
     13)
105    format(i4,1x,f7.5,1x,2(1x,f7.3),3(1x,f7.3),2(1x,f8.3),1x,f6.3)
110    format(3x,a1,4x,a4,5x,a4,3x,a4,4x,a4,6x,2(a3,4x),a5,6x,a3,4x,a4)
120    format(16x,a5,2x,a5,5x,a3,6x,2(a3,4x),a5,5x,a5,4x,a3)
       return
500    close(2)
501    return
       end
```

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FLOWCHART OF INERACTIVE COMPUTER CODE INJFLOW

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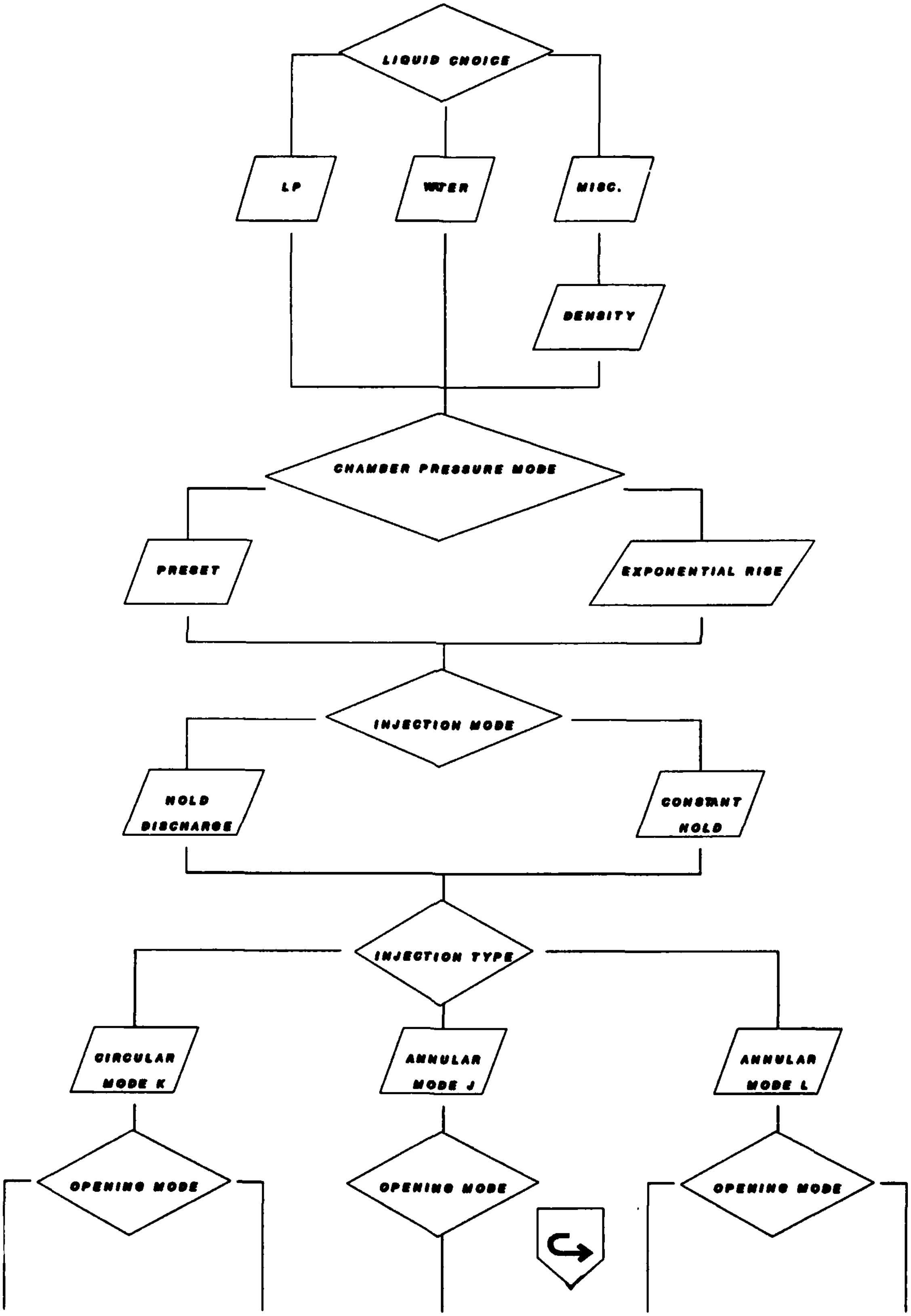
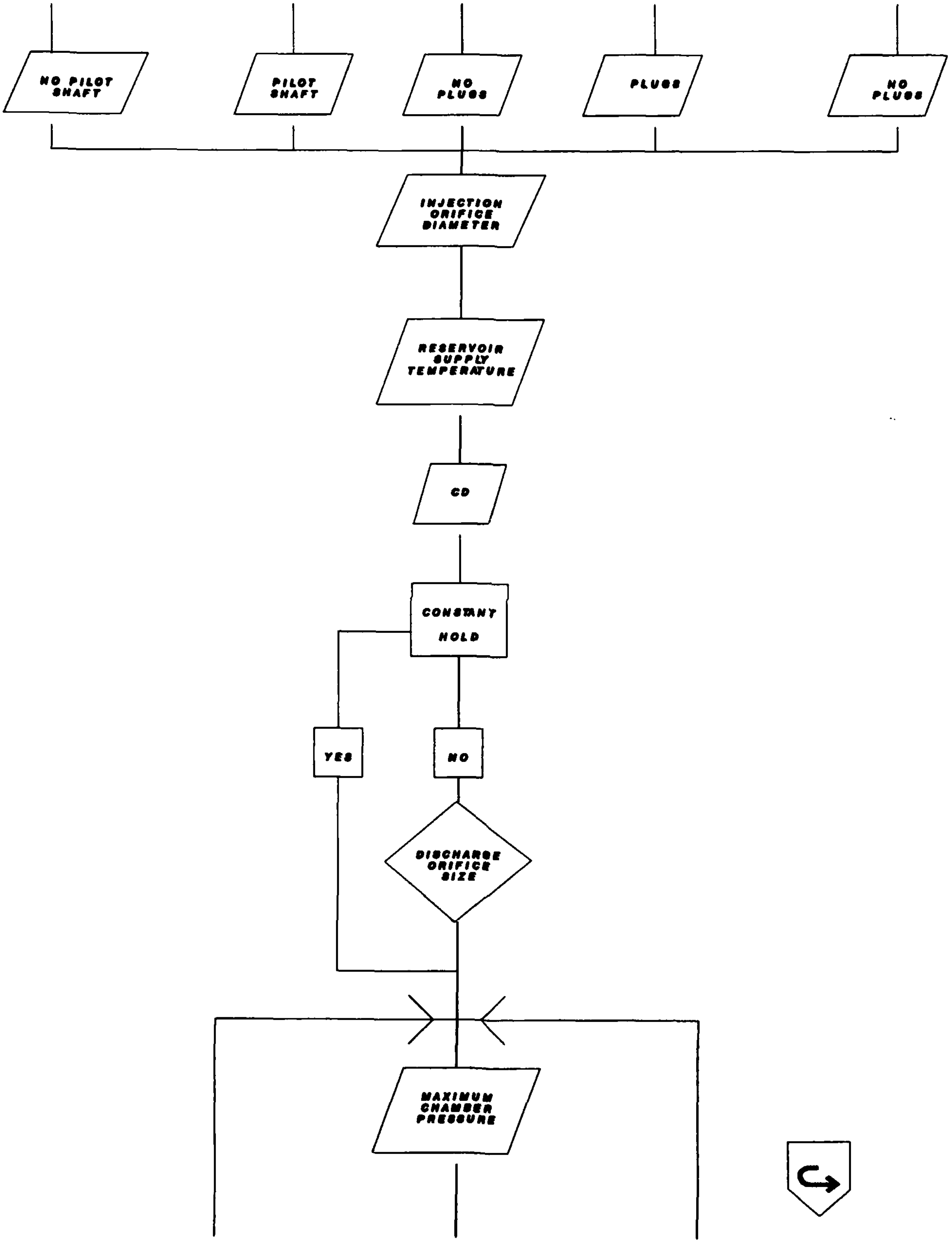
APPENDIX B: FLOWCHART OF INTERACTIVE COMPUTER CODE INJFLOW

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PLUGS
NO PLUGS
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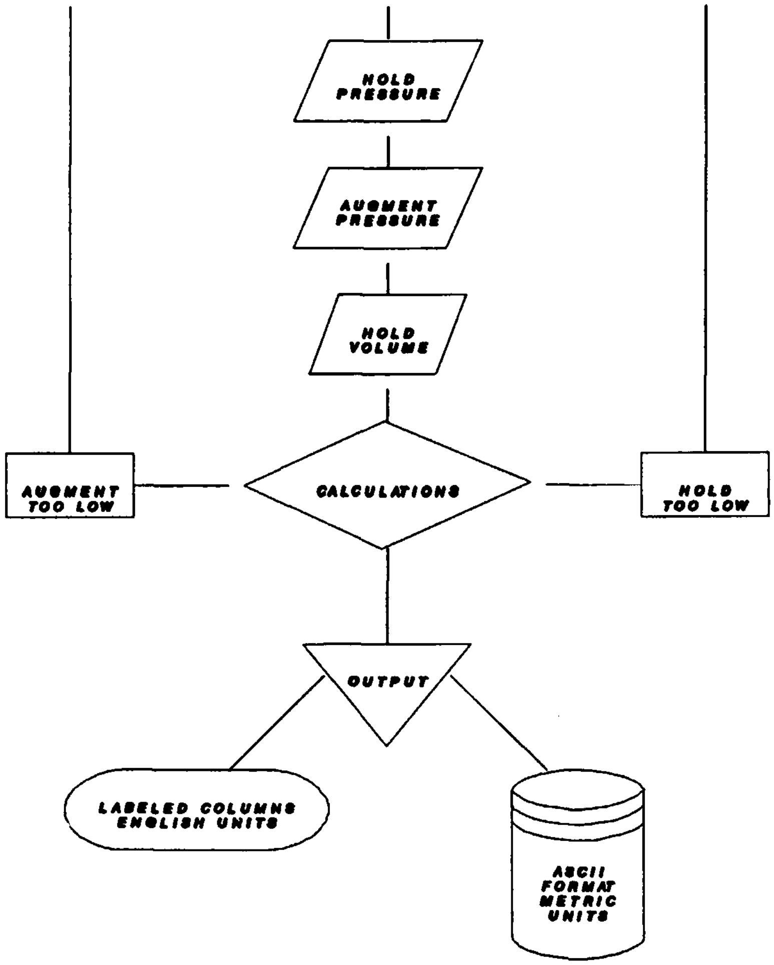
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